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A Basis for Understanding Fishery Management Complexities

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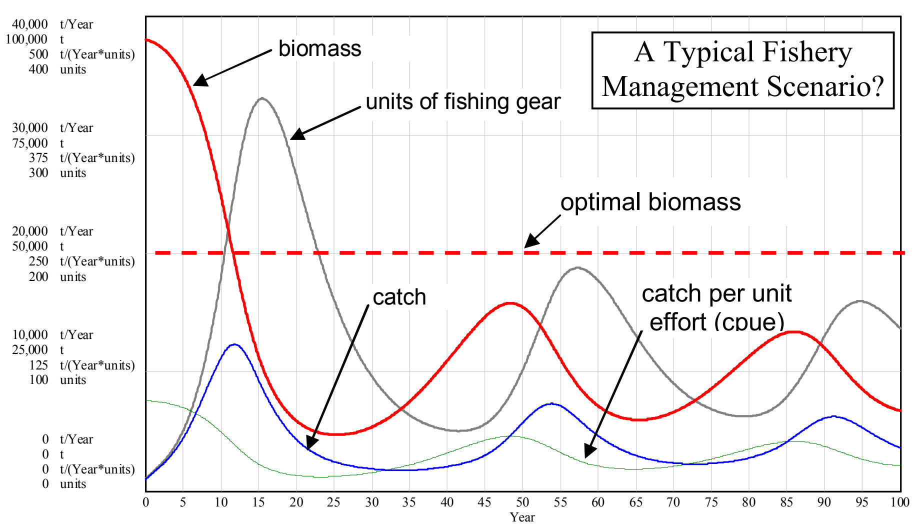

A Basis for Understanding Fishery Management Complexities [1]

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Abstract

Many fisheries in developed countries are seriously over-harvested in spite of the efforts of dedicated scientists and management agencies and a concerned public. Many of these fisheries are well studied – lack of data is not the primary problem. Complexity with the fisheries and management systems conspires to defeat seemingly obvious solutions.

System dynamics modeling may help provide solutions via its transparent framework for describing and analyzing the complex decision making systems. In fisheries, such system descriptions often become enmeshed in the many aspects of fish population dynamics and fail to adequately describe decision making activities of fishers, management agencies, and politicians. This paper is an attempt at providing a simple, but acceptably complex, population model meshed with both fishery activities and management decision making.

The model is based on the well-known Schaefer biomass dynamic model but allows for delayed entry of young into the fish stock and for biomass feedback to rates of addition to the stock due both to growth and entry of young fish. Fishers enter the fishery only if catch rates are sufficiently high. When catch rates are low remaining fishers attempt to improve their fishing efficiency. Excessive fishing also can damage the ecosystem's ability to support the fish population. Managers attempt to maintain the fish stock at acceptable biomass levels, but their efforts are influenced both by lobbying by fishers and by politicians' varying support for management.

1 Introduction

Poor resource management is not only a problem of the developing world. Many marine fisheries in developed countries are seriously over-harvested. Canadian cod fisheries have not recovered after a completely unexpected collapse (Roy 1996). Closures in the North Sea have also been implemented (Malakoff and Stone 2002). In 2001, the US government determined that 33% of its commercial fish stocks of known status were over-fished (National Marine Fisheries Service 2002). Over 80 marine fish species or stocks are vulnerable, threatened, or endangered with extinction from North American waters (Musick *et al* 2000).

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These countries have some of the world's most sophisticated scientific communities dedicated to good fisheries management. Members of this community, most members of the fishing industry, as well as political and governmental entities involved in fishery decision making, all strive to make good decisions. Yet these decisions have largely failed to prevent over-fishing. Why?

Is scientific information lacking? Although good data is essential, it is unlikely that even more data will lead to significantly better decisions. In fact, some of the best biological and fishery statistical information is associated with those fish stocks (e.g., cod) having the most difficulty. In any case, we can't expect to have perfect knowledge for all fish stocks on a timely basis. In the USA, sufficient data exist to determine abundance in only about one third of the 959 identified commercial fish stocks. In fact, data regarding abundance or fishery status are available for only 40% of "major stocks" (National Marine Fisheries Service 2002).

A number of authors have examined the causes of fishery management failures. Some of these have focused on our lack of sufficient knowledge of biological and climatic mechanisms affecting fish stocks. Others have examined specific failures in decision making mechanisms, such as the failure to implement needed restrictions on fishing in a timely manner due to social or economic pressures. A few researchers have attempted to examine how the complex mixture of biological, social, economic, and environmental information affect fishery management decision-making processes.

The fishery decision-making system is highly complex including elements of biological, economic, social, ecological and physical spheres. Elements of each sphere affect elements of the others causing numerous feedbacks. These feedback loops remain largely unexamined during the decision making process. Of necessity the decision process focuses on expected benefits via specific decision pathways.

Inevitably unintended consequences arise from these decisions. As catch rates decline, for example, the rate of violation of regulations may increase as fishers try to maximize their ability to pay off debts in a declining industry. Such violations create unreported catches further decreasing the reliability of fishery data which are the basis for decisions. Declining catches, and certain fishery restrictions, stimulate more effective fishing strategies. Such feedbacks conspire to defeat the good intentions of decision makers.

One overriding influence derives from the lag times needed for economic and ecological systems to come into equilibrium, if such equilibrium actually exists. Fishery overcapacity develops before over-fishing becomes apparent. Excessive fishing capacity is then supported by economic and associated socio-political concerns. Actions to lower capacity become problematic. If the fishery rebounds additional overcapacity develops (Hennessey and Healey 2000; Ludwig *et al* 1993).

Some suggest that the very complexity of the system contributes to its failure. For example, efforts to make fishery regulations more equitable increases the number of special regulations for particular user groups, which makes enforcement more complex and difficult, and further increases non-compliance. As the system becomes more complex uncertainties increase, making desirable outcomes less likely (Healey and Hennessey 1998).

An increasingly complex decision making environment also increases the likelihood of litigation. This causes, at best, significant time lags in imposition of regulations. At worst proposed regulations are reversed causing additional confusion for regulators and fishers. In the USA in the 1970s and 1980s only one or two court challenges were made to NMFS rulings annually, but in the late 90s this rose to more than 10 per year reaching over 20 in 2001 (Gade *et al* 2002).

Uncertainty in fishery data and climatic variables affecting fish stocks is a source of additional complications for decision makers dealing with fishery systems. While use of Baysian statistics has improved our ability to understand probable outcomes of management decisions, the incorporation of uncertainty into the management regime is still problematic (Charles 1998; Cochrane 1999; Lane and Stephenson 1998). Lauck (1996) investigated the use of hedging in fishery management, but the increasing complexity of fishery management systems conspires to limit such options to address uncertainty. The multiplicity of regulations under complex management regimes can limit fishers' options to counteract uncertainty (Hilborn *et al* 2001). As uncertainty increases, sustainable management requires significantly lowered allowable catches (Walters and Pearse 1996), but these may be politically difficult to implement.

As Gade et al. (2002: xi) state, discussing problems in the USA, "In a real sense, the fisheries management system is in disarray. Management is increasingly exercised by the courts through litigation, by Congress through its annual appropriations and reports, and by constituencies that seek redress through these forums."

The need to examine fishery systems holistically has been pointed out by several authors. Walters (1980) highlighted the importance of viewing fisheries as dynamic systems with interacting biological, political, social and economic components. Anderson, in his discussion of "bioregunomics", specifically included lobbying of fisheries agencies by industry to influence policy, as well as the function of courts as arbiters, as part of a needed new paradigm for fishery management (Anderson 1984, 1987). Recently Charles structured a book around the concept of fishery systems, and included in that concept management decisions and the response of fishers to them (Charles 2001).

It is important to point out that complexity in fishery management exists not only in its detail, but in its dynamics. Dynamic complexity arises for many reasons associated with the causal links between components of the system (e.g., see Sterman 2000: 21-22). It is not just that the system is composed of many components, but that a change in any one component will cause a cycling reaction in the others.

At present fishery management entities are becoming more aware of problems of complexity in the decision making system and decision makers are extending their analyses beyond bio-economic issues. There is an opportunity to modify management approaches to address issues created by the complexity and uncertainty inherent in the fishery management system. To do this several questions must be answered: How can fishery decision making systems best be analyzed? How can these analyses sufficiently account for complexity and uncertainty, and still provide meaningful, sufficiently detailed decision and policy direction? How can the complex consequences of management decisions be better predicted by inclusion of factors beyond the realm of fish population biology?

2 The Model [2]

There is a need for models that allow us to examine complex fishery issues in a transparent and understandable manner without becoming overly involved in details of population dynamics. For this purpose it is also good to have a standardized starting point for the biological aspects of the model. The Schaefer biomass dynamic model and its modifications, are well known in fisheries, and are relatively easy to understand, especially when put into a system dynamics (SD) format. A series of modifications to the basic model can allow us to examine the effect of various fishery management policies within a complex framework. Herein I do not wish to focus on details of fishery biology but rather attempt to provide a starting point for examining complex interactions between social, political, economic and environmental issues. System dynamics modeling supplies the needed framework for doing this.

The overall purpose here is to examine the use of the biomass dynamic model as a basis for modeling the bigger picture of socio-politico-economic interactions. However, to accomplish this goal, we will first consider some useful modifications to the original model formulation.

2.1 The basic model

The typical formulation of the Schaefer model (Schaefer M. B. . 1954; 1957) equates the rate of change of population biomass to inflows of biomass minus biomass outflows. It is typically presented as follows:

$$\frac{dB}{dt} = rB\left(1 - \frac{B}{k}\right) - qEB$$

From a system dynamics perspective it is best to write it as:

$$\frac{dB}{dt} = rB - rB\frac{B}{k} - qEB$$

Here the rate of change of fish biomass over time is seen to be composed of an inflow, and two outflows. Increase in population biomass, is a single inflow due both to growth and to the addition of new fish. It is equal to the biomass fractional growth rate *r* times the existing biomass *B*. Natural decrease in biomass is indicated by *–rB*

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[2] This section builds on information presented in Dudley, R. G. and Chris S. Soderquist. 1999. A Simple Example of How System Dynamics Modeling Can Clarify, and Improve Discussion and Modification, of Model Structure. Presentation to the 129th Annual Meeting of the American Fisheries Society, Charlotte, North Carolina. August 1999.

multiplied by the ratio of *B* to *k,* where k is the maximum possible population size. This causes natural death rate to decline as biomass declines.[3] The outflow of population biomass caused by the catch is indicated by the instantaneous fraction of fish biomass caught by each unit of fishing gear *q*, times the number of gear units[4] *E*, times the biomass *B*.

In system dynamics format the model is as illustrated in Fig 1. It is interesting here to point out the difference in philosophies between the original formulation and the system dynamics approach. System dynamics modeling emphasizes changes over time. Also, the system dynamics modeler generally tries to formulate each component of a model separately, then defines the structure linking components. Mathematical modelers, on the other hand strive to develop one summary "elegant" equation that will calculate an answer for a particular set of inputs. Other forms of modeling are, perhaps, somewhere in between. Presented as a system dynamics stock and flow diagram the structure of the biomass dynamic model is clear. The mathematical formulation of each component is also explicitly stated.[5]

The biomass dynamic model was originally developed to calculate equilibrium yields under given conditions.[6] System dynamics models, on the other hand, typically are used to gain an understanding of system behavior over time. Typical outputs from the model for a selection of fishing pressures illustrate the traditional parabolic curve of equilibrium catch vs. biomass (Fig. 2).

Importantly, because calculations are carried out numerically, modification to the system dynamics version of the model is not limited by analytical tractability. The model structure can be modified to examine increasingly dynamic and complex situations. Note that there have also been various non-SD approaches to modifying the model (e.g., see Prager 1994).

2.2 Adjusting the basic model

2.2.1 Providing for recruitment delays

The strength of the biomass dynamic model is its simplicity. It avoids the use of detailed age structure which in many instances is not needed. However, the standard model treats additions of biomass to the stock as a single flow with no provision for separate consideration of increase in stock biomass due to growth and increase due to recruitment (i.e., addition of new fish to the stock). We may wish to include the effect of delays in recruitment because young fish often become a part of the fishable stock only after several years (e.g., at age 4). This delay is particularly important in the fairly typical situation where large inter-annual variations in recruitment occur,

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[3] Excluding catch, this form of the model is mathematically identical to the classic logistic model of Verhulst (1838). However, that model considers net growth in numbers (rather than biomass) and does not explicitly partition growth and mortality. One could argue, for example that losses represent not only deaths, but lost (potential) growth as well.

[4] Note that units of fishing gear can be variously defined as boats, nets, hooks, traps, etc.

[5] See appendix for model equations.

[6] An important aspect of the biomass dynamic model is that data needed to determine its parameters are relatively easy to obtain. Necessary data can be obtained from a fishery, without the need for determining abundance of fish of different ages.

and in heavily fished stocks where "recruits" account for a significant proportion of the total fish biomass.

Delays in the recruitment of new biomass to a population can be incorporated into the model without resorting to an age based approach (Fig. 3). Here recruitment is envisioned as the biomass of fish newly entering the fishery. In this formulation we largely ignore what actually happens to young fish prior to their entering the fishable stock, except that large variations in recruitment can occur. That is, the size of the stock *delayed recruitment* indicates recruitment expected at a future time. Although alternate formulations might attempt to accurately model the biomass of young fish as a fully connected part of the model, additional detail would be needed to account for rapidly changing growth and mortality rates during early life. Nevertheless, a true two stock model may be appropriate in some cases.

See comments below about the shape of the relationship between the stock biomass and amount of recruitment.

2.2.2 Partitioning delayed and non-delayed additions to biomass components

If we wish to account for delayed recruitment additions to a stock, we should also account for non-delayed stock increases due to growth of biomass already present. This can be accomplished by having additions to the stock composed of two components and by having the *fractional growth rate r* partitioned into a growth and a recruitment component (Fig 4).

A question then remains: how much of the addition to a stock is due to recruitment, and how much is due to growth of biomass already present. This is an important issue because dynamics of some stocks are dominated by large fluctuations in year-class size. For the time being we will leave this question unanswered and will assume that the proportion of additions to biomass due to recruitment is in the range of 30 to 70 percent, with the higher proportions more typical of short-lived fishes. At a later point in model development we may wish to examine feedback factors which affect this proportion. Two components likely to have a feedback effect on this relative proportion are the fractional rate of increase itself and fishing intensity.

2.2.3 Biomass feedback to additions to biomass

The standard model responds to any decrease in relative biomass, including decreases due to fishing, by lowering the fractional rate of natural decrease in biomass and thus the death rate. We must consider, however, that any decrease in stock biomass below the "virgin" stock size might also cause an increase in growth and reproductive success – on the additions side of the model. We would expect this because decreases in population density should improve conditions for growth and reproduction for remaining fish.

Also, from experience in the real world we know that mean age of biomass in a stock will decreases with increasing fishing pressure.[7] However decreases in stock size in

[7] Typically this evidence is manifested as a decrease in average age of individuals in the fish stock. In fact, the mortality rate is often determined by the slope of a graph of numbers vs age. If the mortality rate rises the relative abundance of older fishes decreases.

the standard biomass dynamic model do not alter mean retention time in the stock. We know this because, in equilibrium the inflow to the stock must equal the sum of the outflows. In equilibrium both fractional rate of additions and total death fraction (death fraction plus catch fraction) are equal to r. Thus at equilibrium mean residence time in the stock will always equal 1/r which is constant.

A modification to the model which adjusts the growth rate, r, upward as biomass in the stock decreases seems appropriate. The forms which this feedback might take are several, but we expect that r will increase somewhat as the stock is diminished and will decrease somewhat as relative stock size increases. This will also cause average age of biomass in the stock to drop as we would expect.

One convenient formulation is to allow *effect of biomass ratio on r* to be 1.0 (r keeps its original, typical, value) when B/k is 0.5, to have this effect increase linearly by some small amount (perhaps 10% to 30%) as *B/k* approaches zero, and to decrease by a similar amount as *B/k* approaches 1.0 (Fig. 5). With this formulation, as the stock biomass decreases effective growth rate will increase, and mean age of biomass in the stock will decrease. The strength of this effect will undoubtedly vary among populations.

Combining this feedback from the stock biomass ratio with the partitioning of growth and reproductive additions to the stock gives us the final formulation for the fish stock aspects of the model (Fig. 6). Note that in keeping with the concept of the original model, that the unmodified death rate should equal the growth rate, the basic fractional death rate should now equal the *average growth rate* which is a weighted average of the modified rates for growth additions and recruitment additions.

2.2.4 The effect of stock size on recruitment additions

If we opt to allow separate growth and recruitment additions to biomass as indicated above, then we need to be concerned with the shape of each of these relationships. In the standard model *additions* to biomass is a fixed fraction of current biomass. However, the relationship of stock size to amount of recruitment has been intensively studied, and a direct proportional relationship of biomass to recruitment amount is clearly not realistic. In general a curved relationship with either stable or decreasing recruitment at high stock biomass levels is typical. It would be reasonable for a graph of recruitment amount vs. biomass to look like lines B or C in Fig 7.

The shape of the graph of growth additions as biomass increases to maximum level is likely perhaps to be more like line A in Fig. 7.

2.2.5 The completed fish stock portion of the model

At this point the model, still without fishery or management components, allows for both: 1) the partitioning of growth additions and delayed recruitment additions to the stock and 2) feedback from current biomass ratio to stock additions.

2.3 Adding fishery components

Prior to any attempts at modeling management decisions, development of a model of an unmanaged fishery seems appropriate. This model, in addition to the simple stock dynamics shown above, allows for: 1) the entry and exit of vessels from the fishery in response to fishing success, 2) the accelerated improvement of fishing gear when catch rates drop, and 3) the possibility of fishery damage to the underlying ability of the ecosystem to support the fish population.

2.3.1 Catch per unit effort determines vessel numbers

Typically vessels[8] enter a fishery because profits appear attractive. Normally profits are linked to some acceptable level of catch per unit of fishing effort (referred to as cpue) which provides sufficient monetary return over and above total costs of fishing operations. We can assume for our purposes here that some acceptable cpue is the minimum level of catch that attracts vessels to the fishery. If the actual cpue falls below this fewer new vessels will be attracted and there will be a net loss of vessels from the fishery. As cpue rises above this critical level more vessels will be attracted to the fishery. If cpue falls well below the acceptable level, vessels' retirement from the fishery will also be accelerated (Fig. 8).

The acceptable cpue level implicitly incorporates factors related to profitability of fishing such as cost of operations and investment, and the expected price of the fish caught. Another model sector could later be added to explicitly examine how these factors affect acceptable cpue.

The question of capacity utilization is only partially dealt with here. For the most part the model assumes that vessels are all used at 100 percent capacity if they are participating in the fishery. However, a test sub-section of the model examines the effect of recent cpue on capacity utilization. Recent cpue levels (say over a few weeks) will influence whether a fisher (who is still participating in the fishery) will put in more or less effort. However, the nature of this relationship is unclear. If cpue levels are high, additional effort will be made to catch fish while the fish are abundant. On the other hand if cpue drops somewhat below acceptable levels then additional efforts might also be made in an attempt to maintain cpue at the acceptable level. Nevertheless, if cpue drops well below acceptable levels then fishers will lower the use of their fishing capacity.

2.3.2 Vessels maintain catch rates by increasing efficiency

When catch per unit effort drops below acceptable levels fishers who remain in the fishery will respond by attempting to improve the efficiency of their fishing gear. These improvements may be in the form of better application of known technology (e.g. using their sonar more effectively) or applying recently developed techniques (e.g. adjusting fishing gear design). We can assume that at any given time some small amount of improvement, maybe 5% to 20%, to existing gear efficiency is possible. Importantly, these improvements gradually become absorbed into standard fishing practice and therefore will permanently increase gear efficiency slightly. Over time these small changes in gear efficiency will accumulate (Fig. 9).

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[8] I have used "fishing vessels" as the unit of fishing gear. However, units of fishing gear could be defined as number of nets, traps, hooks, etc. Here I use the term 'vessels' in this general sense.

2.3.3 Fishing decreases carrying capacity

In some fisheries, fishing activity can decrease ecosystem carrying capacity. The most widely cited example of this phenomenon is the damage which trawling gear inflicts on the bottom habitat of groundfish.[9]

Presumably damage to carrying capacity is cumulative and is proportional to the amount of fishing taking place. This idea is incorporated into the model. Here each effective fishing unit inflicts a small amount of damage on the habitat. This damage in turn affects the maximum possible biomass which the habitat can support. It can also be assumed that there is a habitat recovery time of several years, perhaps tens of years in the case of serious physical damage. Further, we can assume that the rate of recovery will be slower if habitat damage is extensive (Fig. 10).

2.4 Adding management strategies

2.4.1 Management attempts to maintain optimum biomass by adjusting fishing gear numbers

In this paper I have opted to take a fairly simplistic approach to management of the fishery in which a management entity strives to maintain the fish stock at a fixed fraction of its un-fished biomass. One typical target value for management would be at one half the assumed virgin (i.e. unfished) stock.[10] In the model this idea is captured as indicated in Fig. 11.

Management formulates a revised perception of stock health based on recent stock assessment information. If the stock estimates are near the desired level the new perception is neutral: the stock is in reasonable health. If new data indicates that the stock size is greatly different from the desired size then the new perception of stock status is revised upward or downward accordingly (Fig 12). Based on this new information management's perception of the fishery is gradually changed. Management's perception of the fishery then determines the desired changes in fishing gear numbers. If the perception of the stock is negative a fractional decrease in gear numbers will be proposed. If perception of the stock is positive the suggested fractional change will be positive. These fractional changes become greater the further management's perception is from neutral (see Fig. 13). A change in fishing gear numbers is then proposed to be implemented over some implementation time, and if management proposals have the force of law, the proposed changes in fishing gear numbers are fully implemented.

2.4.2 Fishery Conflicts and Political Lobbying

Typically fishery management entities cannot merely dictate changes in fishing effort. Many social, economic, legal and consequent political issues come into play. Fishers lobby for more liberal regulations. Environmental groups lobby for more restrictive

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[9] For some interesting examples see the special section in *Conservation Biology*, Vol. 12, No. 6. Dec., 1998: Effects of Mobile Fishing Gear on Marine Benthos.

[10] In theory this is the point where the sustained biomass of the catch is maximum. See the figure earlier in this paper. However, if there is feedback from biomass ratio to the growth rate as described in the text, then the stock level where the catch is maximum will be somewhat below 50,000 t.

regulations. Both groups may seek political backing for their particular view. If this is unsuccessful then either group may seek redress in the courts.

In this paper I look only at a simplified version of the first of these scenarios where fishers and managers will both work to have their own desired adjustment to fishing gear numbers implemented. In the model this aspect of the fishery is handled in two ways. Firstly a negotiated vessel entry rate is calculated as a weighted average of the two desired rates. The weighting is based on the relative strength of management's views. Secondly, there is an option of allowing an increasing level of lobbying as management's and fisher's views diverge (Fig. 14). If the view of the two parties diverges considerably then, in the model, lobbying can reduce management's current effectiveness by up to 50 percent.

The relative strength of management's views may also be influenced by politics. As the fishery becomes obviously over-fished in the eyes of politicians, the management agency will be given strengthened authority. In the model the politicians' views are represented by an indicator of the need for stronger management: the relative size of current fish catches compared to fish catches in the past. Low recent catches compared to the longer term "historical" catches will result in more influence for the management entity and its views.

Overall this model, in a general sense, embodies a concept of fishery management whereby managers view success in terms of stock level, fishers view success in terms of catch per unit of gear, and politicians view success in terms of catches which should be at least as good as they were in the past.

3 Model Outcomes

Here we will use the example of a typical fishery for a moderately slow growing species with starting parameters as indicated in Table 1.[11]

3.1 A fishery with no management

When vessels first enter a new fishery, catch per unit effort is well above the level necessary to attract additional participants to the fishery. As more fishers enter the fishery, fish stock biomass starts to drop as does catch per unit effort. Even though both stock biomass and cpue are dropping, catches continue to rise due to the continuing influx of new participants to the fishery. Catch per unit effort eventually drops to unacceptable levels in about year 12 and, with a slight delay, vessel numbers in the fishery also start to drop. By this time the fish stock is already seriously over-fished as too many vessels had entered the fishery. Even though participants now rapidly exit the fishery, cpue and catches continue to drop until year 20 and 30 respectively (Fig. 15).

Once cpue rises high enough to attract more fishers the cycle starts again. Because of the decreased fishing, fish stocks have already started to recover by year 21, and by year 33 participants are returning to the fishery in increasing numbers. However, stock biomass never gets the chance to recover to its former size. This is because

[11] For default settings of these and other model constants see model equations.

new participants are joining the fishery well before the stock has a chance to recover. Also fishers have increased their gear efficiency during the period when cpue was low. The third and subsequent cycles are progressively less productive. Note that model outcomes are highly dependent on a number of input parameters, some of which are discussed below.

If we start with an over-fished stock (rather than the virgin stock as above) the results are similar to the second and subsequent cycles above.

3.2 Managing the fishery

Management in the model, as described above, consists of monitoring the fish stock and making fractional changes to fishing gear numbers entering the fishery if stock size is above or below the desired size (as indicated in Figs 12 and 13). ‘Perfect’ management[12] implies the full acceptance of management’s recommendations without feedback effects from fishers’ lobbying or from politicians’ concerned about maintaining catches. This simple form of management will gradually increase fishing until stock size drops to the optimal level (Fig. 16). If starting from an over-fished state, perfect management overprotects the stock for a fairly long period before it settles toward the optimum level (Fig 17).

If, realistically, various forms of lobbying take place, then the situation is different. Both forms of feedback induce oscillations similar to those in the unmanaged situation even when the base level of management is 100% effective (Fig. 18). Here we see that all these scenarios manage better than the unmanaged situation, with smaller oscillations having longer periods.

A typical and more realistic situation will have management authority less than perfect, perhaps at 70%, for example. That is, usually management can be expected to be successful in implementing 70% of its suggested change to gear numbers. Also typically, this weakened authority also will be affected by lobbying by fishers and by varying support from politicians (as described above).

Under this ‘typical’ scenario (Fig 19) the fishery will have substantial fluctuations, although these are not as severe as when there is no management. In this example the mean of the fluctuating fish stock is at a point slightly less than one half of management’s target stock biomass of 50,000 t.

This example serves to illustrate that using reasonable assumptions it is fairly easy to recreate a fishery situation that is all too familiar to managers and users of such resources. Mangers and fishers and politicians all follow “rules of thumb” that seem reasonable to them but which result in an outcome disliked by all. The question still remains: how can we improve these systems? That is the subject for much additional study.

[12] By perfect here on only mean fully implemented as modeled with management effectiveness at 100%. There are many other possible management scenarios with none actually perfect.

4 Other Comments

4.1 Random variations in recruitment and its effect on decision making

Large variations in recruitment to a fishery are very common, and if incoming fish are a large component of the fish stock, these fluctuations can cause a fairly rapid and significant change in stock abundance which may last several years. This in turn can have large effects on catches, cpue and the entry of new fishers. Here a random uniform pink noise (Sterman 2000) with a mean of zero and standard deviation of 1 is added to the recruitment expected at each time step. When starting with a virgin stock or an over-fished stock this random variation will change the specifics of each model run, but will not change the basic patterns created by typical management (e.g. Fig 20).

However, if a fishery is in rough equilibrium, under careful 'typical' management, large variations in recruitment can stimulate a fishery boom or bust and can lead to boom and bust cycles in the fishery (Fig 21).

4.2 Effects of various parameters

In the above generic examples I have selected parameters which lead to a situation I believe is typical of many fisheries. Other selections will produce vastly different outcomes. A brief examination of these differences provides some insight into causes for different states in a fishery, but a detailed discussion of each of these parameters is not within the scope of this paper.

Populations with a higher basic growth R rate can sustain heavier fishing pressure. The stock modeled has a growth rate of 0.2. Faster growing populations (e.g. tuna) have an R near 0.5, for example, while large sharks and pacific rockfish have R nearer to 0.1.

The overall catch fraction at any given time is the product of the gear efficiency and the number of gear units operating. Higher gear efficiency will result in more rapid over-fishing. Thus the acceptable cpue at which vessels will enter a fishery is also an important consideration. If this acceptable cpue is low new fishers will continue to enter the fishery long after the stock has fallen below the optimum biomass. This is typical of fisheries where fish are of relatively high value (e.g. bluefin tuna) or where operating costs are relatively low. If acceptable cpue is high then little management is needed unless excess vessels are forced into the system.

4.3 Other forms of management to be tested

In the above model, decisions of managers have been based only on fish stock size and its comparison to the standard model's optimum value of half the virgin stock size. But actually even this simple implementation of management's view incorporates a 'flaw' in management's thinking. As modeled, the current stock size is compared to the virgin stock size in an un-fished state. As fishing takes place the actual capacity of the ecosystem decreases so management's 'concept' of 50% of virgin stock is incorrect. When fished the assumed 50% value is actually above 50% of current maximum capacity. Interestingly, this 'confusion' leads to more conservative decision making by management. If management somehow received a regular update on current maximum stock capacity (e.g. area and quality of suitable habitat) then more rapid over-fishing might occur because management would regularly downgrade their estimate of maximum capacity.

There are many other reasonable formulations for management decision making. Here I have even ignored, for example, the direction of change in the fish stock. Management would normally make different decisions at a given stock ratio if the stock were increasing or decreasing.

Also, the management system modeled here relies on management's knowledge of recent stock size. A more sophisticated decision making model should incorporate recommend appropriate fishing levels based on predicted stock sizes and on inaccuracies in those predictions. In this case one would model the stock assessment process itself. In fact, this would be one important component of a final version of the overall modeling venture of examining fishery decision making.

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Figures for "A Basis for Understanding Fishery Management Complexities"

Richard G. Dudley

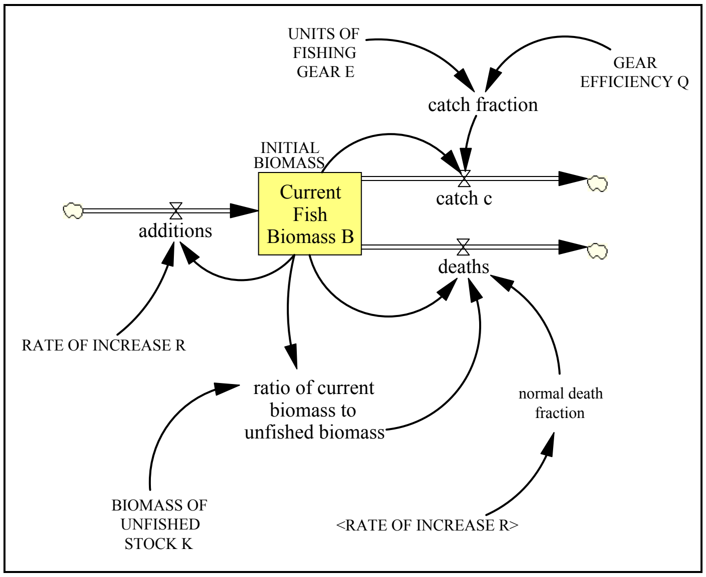

Figure 1. The standard biomass dynamic model of Schaefer presented in system dynamics format. Modifications to this model can form a relatively simple basis for investigating complexities facing fishery management decision making. Letters at the end of each component name refer to the equation presented in the text.

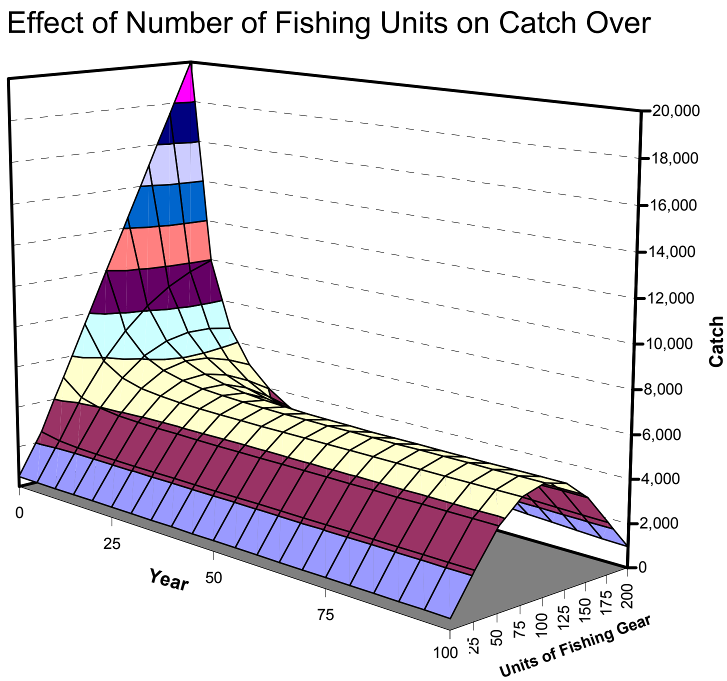

Figure 2. Time lines of catch at different fixed levels of fishing illustrate the shape of the relationship between units of fishing gear and eventual equilibrium catch as produced by the standard model. This curve, shown here at year 100, has the maximum equilibrium catch at an intermediate level of effort which also reduces stock size to one half its un-fished size. The time needed to reach these equilibrium yields can be considerable.

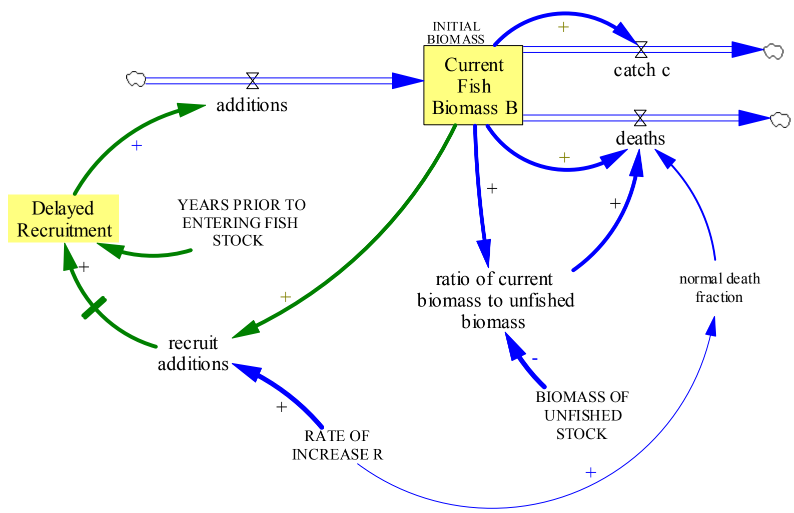

Figure 3. This re-formulation will allow for delayed recruitment (addition of new biomass from reproduction), but ignores additions due to growth.

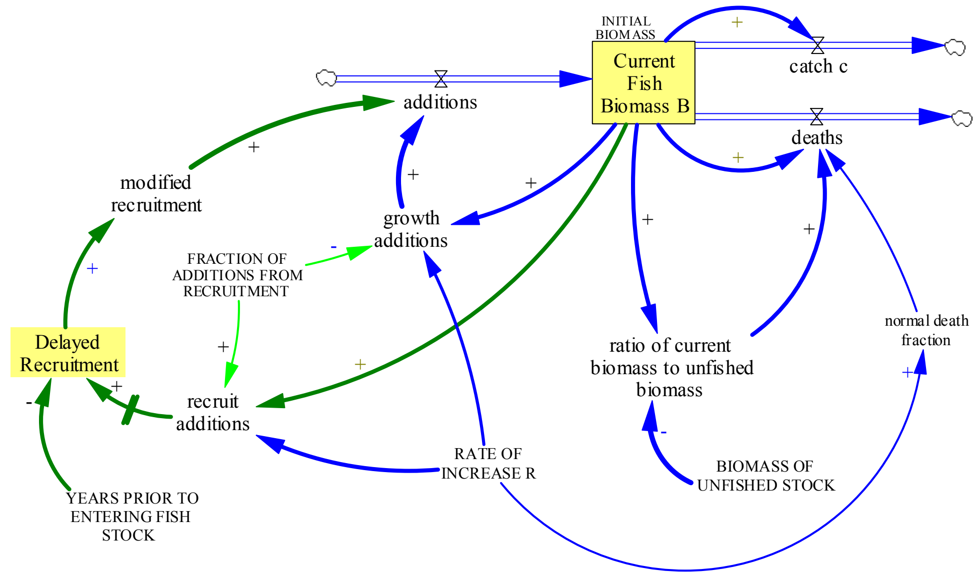

Figure 4. Partitioning of the rate of increase allows for both growth additions and delayed recruitment additions but still maintains the basic logic of the standard model.

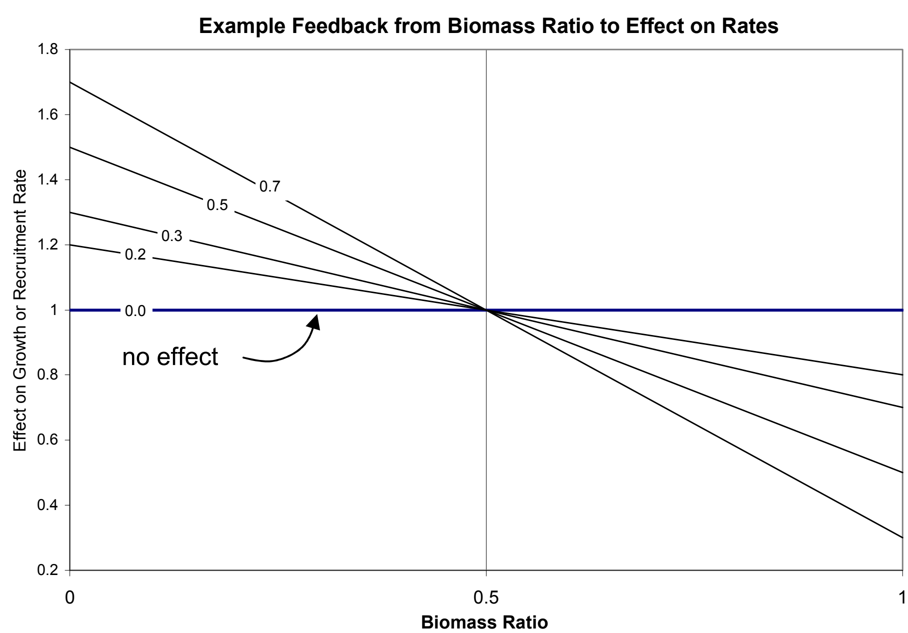

Figure 5. In the standard model biomass ratio has no effect on the growth rate. In the revised model a feedback effect from biomass ratio to growth is proposed. Shown here is a suggested format for such feedback. Each line represents a particular feedback effect, with a feedback effect of zero representing no feedback.

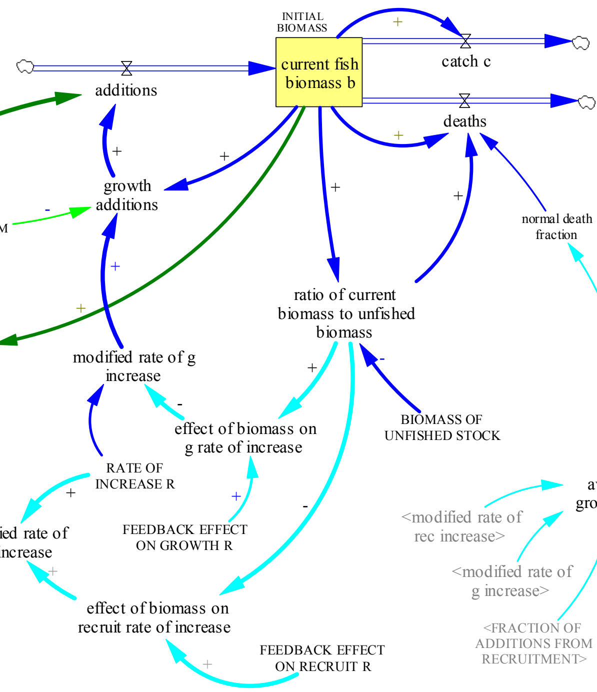

Figure 6. Fully modified biomass dynamic model which allows for partitioned additions due to growth and recruitment and also allows the growth rate of each component to have a feedback effect from population density.

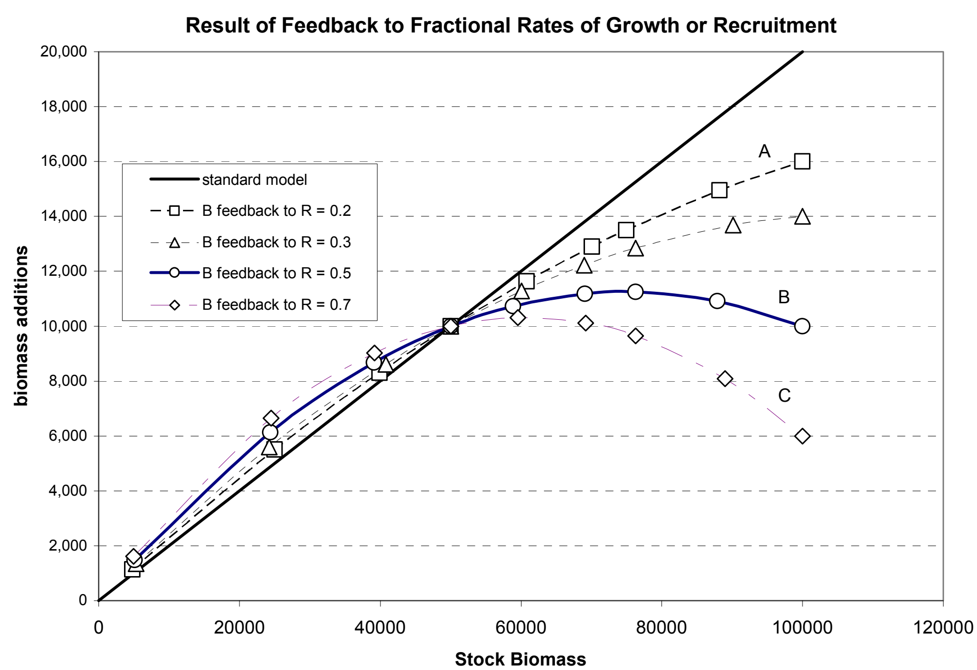

Figure 7. Results of the feedback to fractional rates of growth or recruitment illustrated in terms of biomass additions at given stock biomass levels. Maximum stock biomass is 100,000 tons. Line A might be typical of growth additions to the stock while lines B or C might be more typical of recruitment additions to a stock.

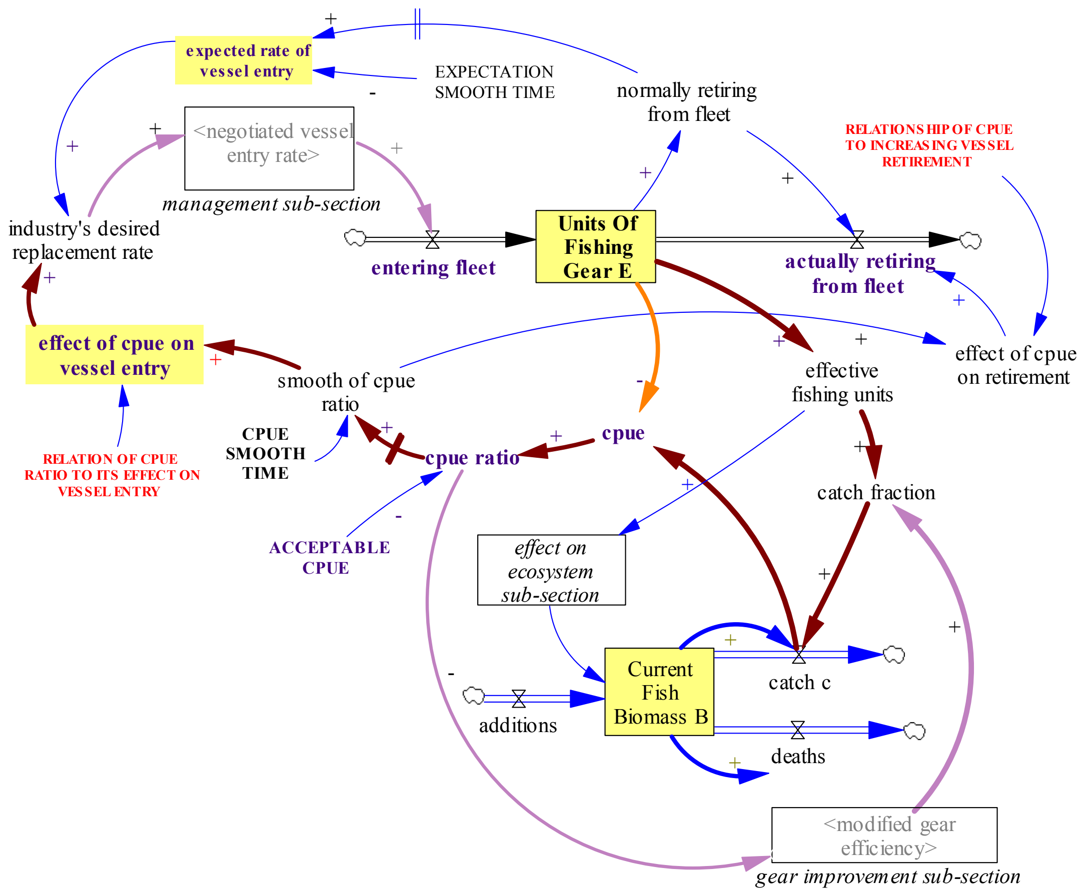

Figure 8. More vessels tend to enter a fishery when catch per unit effort (cpue) is high. A low cpue will both discourage vessels from entering, and will encourage remaining fishers to improve gear efficiency. Also indicated here are links to: 1) management and 2) effects of fishing which degrade the environment's capacity to support fish stocks. For simplicity some model components are not shown.

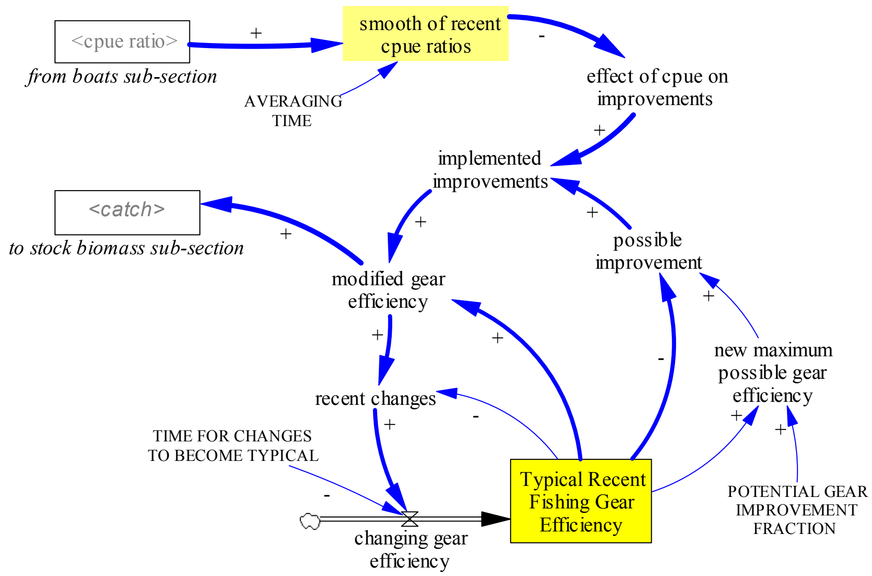

Figure 9. As cpue ratio drops fishers tend to implement strategies that improve the effectiveness of their gear. These improvements tend to be absorbed into what becomes normal gear efficiency. At any given time there is a latent *potential gear improvement fraction*. Thus, over time gear efficiency tends to increase particularly when fishing success is poor. For simplicity some model components are not shown.

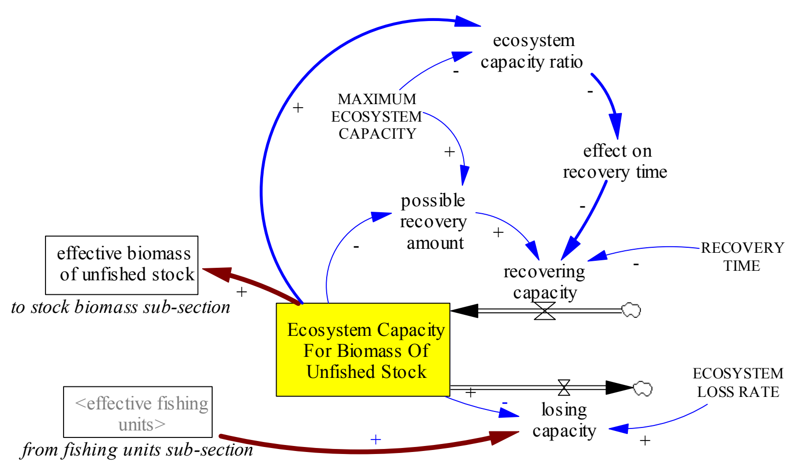

Figure 10. Fishing activity can degrade the environment's capacity to support fish. Once degraded, this environmental capacity takes time to recover. Mean recovery time will be longer if the ecosystem is severely degraded. For simplicity some model components are not shown.

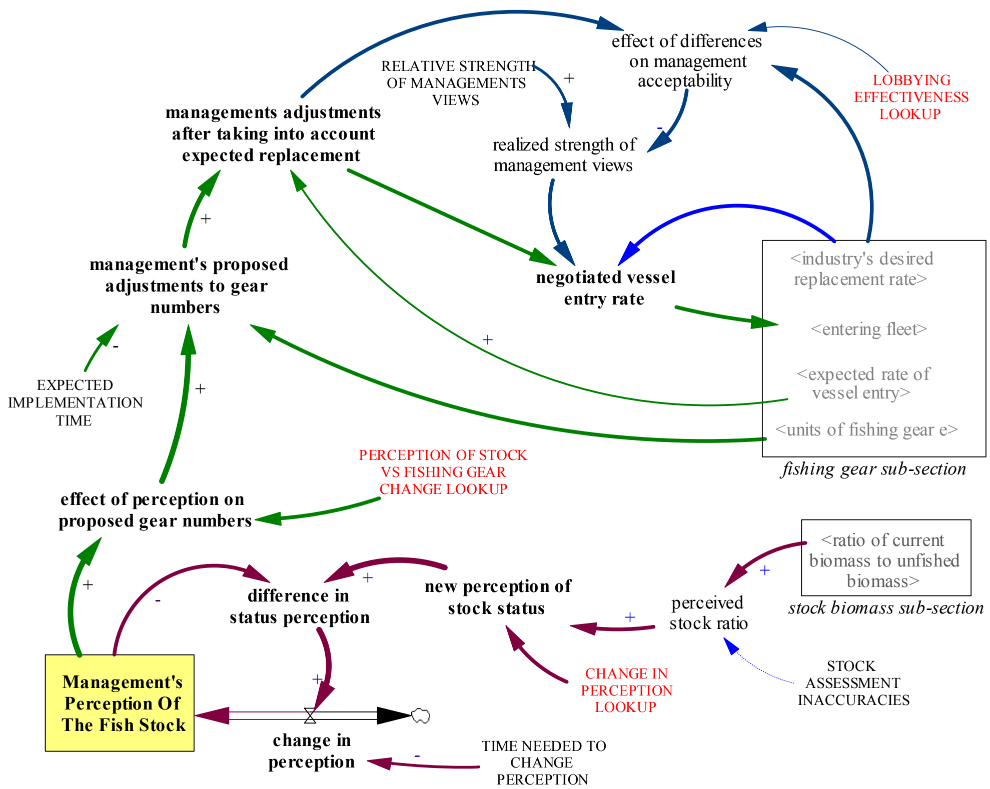

Figure 11. Management's perception of the fish stock status is gradually updated with new data. Based on its perception, management proposes changes to fishing gear numbers. These proposals are implemented subject to the relative strength of management's views. In some cases lobbying will further weaken the views of management especially if differences between management and fishers are large. For simplicity some model components are not shown.

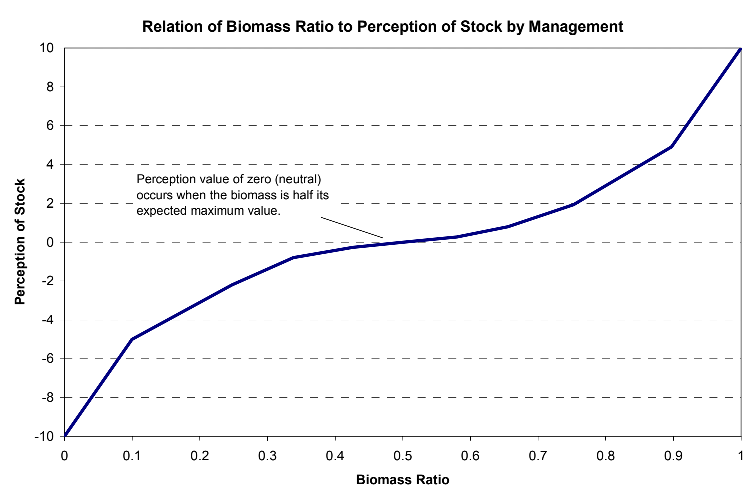

Figure 12. This lookup function describes the effect of biomass ratio on management's perception of stock status. Stock status is described in a range from -10 (heavily overfished) to +10 (unfished). Management believes that stock is being managed well when the biomass ratio is near 0.5.

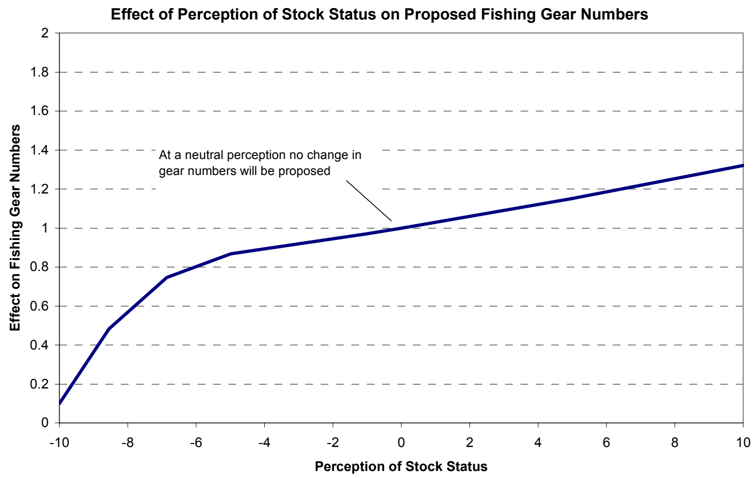

Figure 13. This lookup function describes the relationship between management's perception of stock status and how management feels it needs to change current gear numbers.

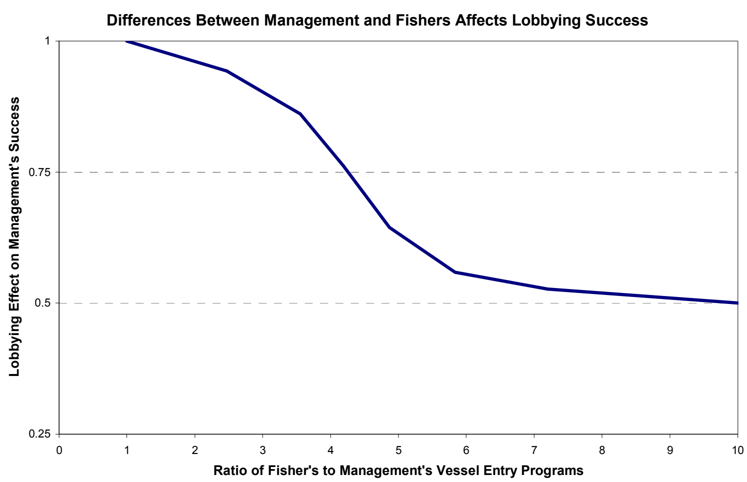

Figure 14. Lobbying can affect the successful implementation of management's efforts particularly if differences between fisher's and management's views are large. This lookup function describes the relationship between the amount of difference in desires for new vessel entries into the fishery and the success of lobbying against management vessel entry proposals.

Table 1. Input values for simulation of a fishery.

Fish Stock	value	units
Rate of increase R	0.2	1/yr
Initial biomass:		tons
virgin stock	95,000	
Over-fished stock	10,000	
feedback effect on growth	0.1	dmnl
feedback effect on recruitment	0.6	dmnl
fraction of additions due to recruitment	0.3	dmnl
years prior to entering fish stock	2	year
Fishery		
initial number of units		units
virgin stock	10	
Over-fished stock	100	
initial gear efficiency	0.001	1/year*unit
acceptable cpue	30	ton/year*unit
average vessel lifespan in fleet	7	year
potential gear improvement fraction	0.1	dmnl
ecosystem loss rate	0.0001	1/year*unit

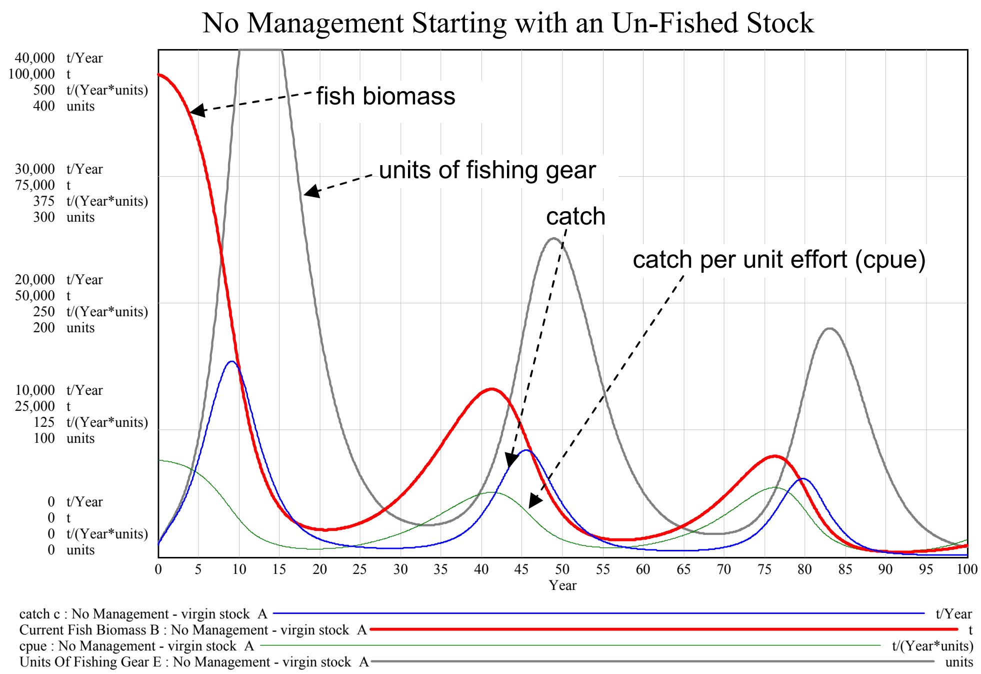

Figure 15. An unmanaged fishery exhibits typical overshoot and collapse cycles with the peak of each cycle somewhat smaller than the previous one. Fishers are initially attracted by high cpue, but over fishing causes the fish stock to collapse. As the stock becomes over-fished enough vessels eventually leave to allow the stock to recover and the cycle starts over. During periods of poor fishing, fishing gear is improved in an attempt to maintain cpue. The fish biomass level where sustainable catches will be highest is slightly below 50,000 tons in this scenario.

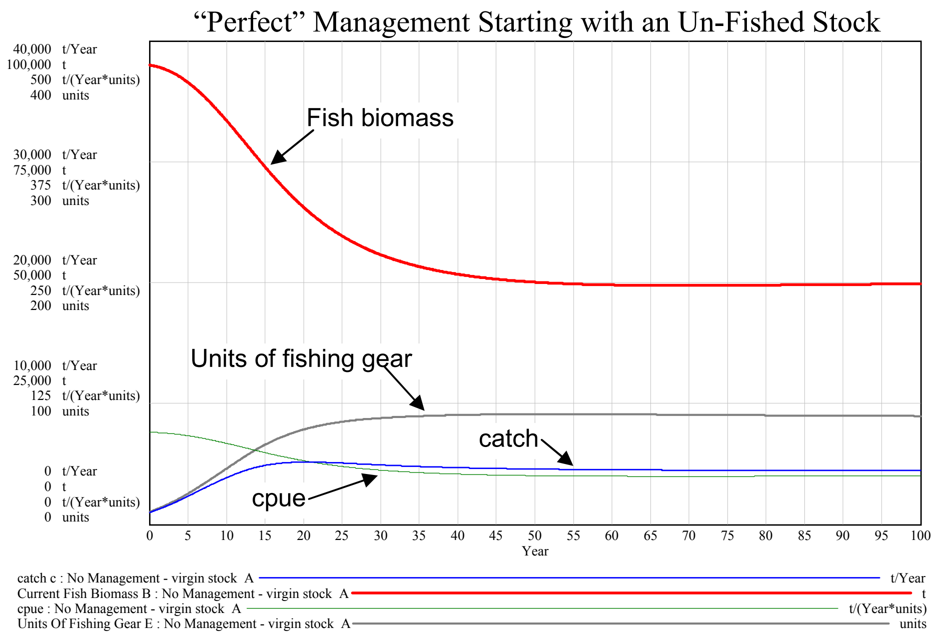

Figure 16. Under 'perfect' management (as described in the text) management efforts gradually bring the stock to levels that maximize long term catches.

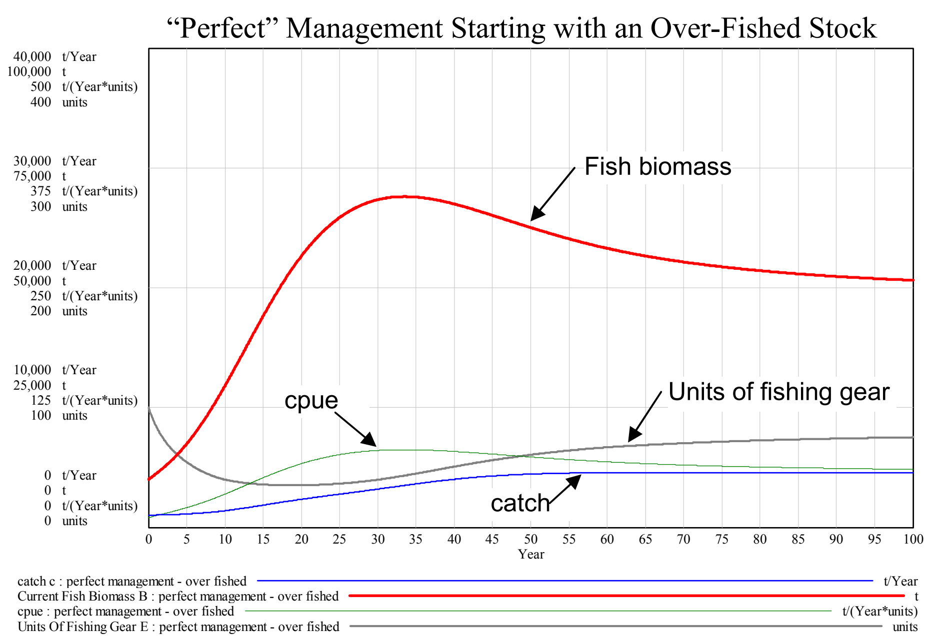

Figure 17. 'Perfect' management starting with an over-fished stock tends to overprotect the stock somewhat prior to bringing it to the presumed optimum level. Catches progress steadily toward the optimum level, but reaching this level takes many years.

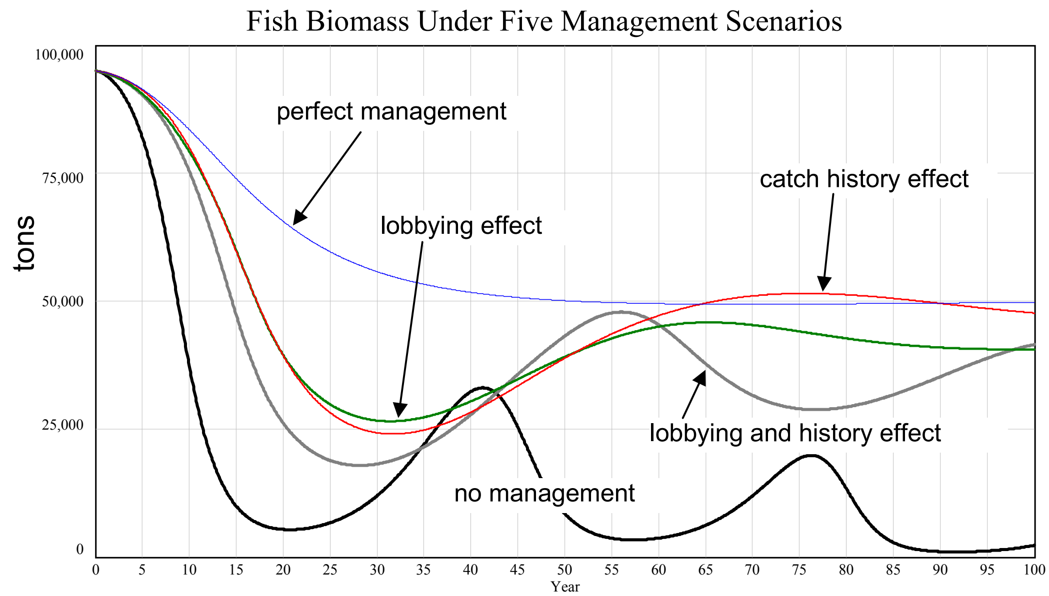

Figure 18. As described in the text, management efforts are effected by lobbying by fishers and also by changes in politicians' perceived need for management as reflected in historical catch trends. Here the fish stock biomass is traced under five management scenarios. In all cases except "no management" the underlying strength of management (without other effects) is 1 (i.e. 100 percent).

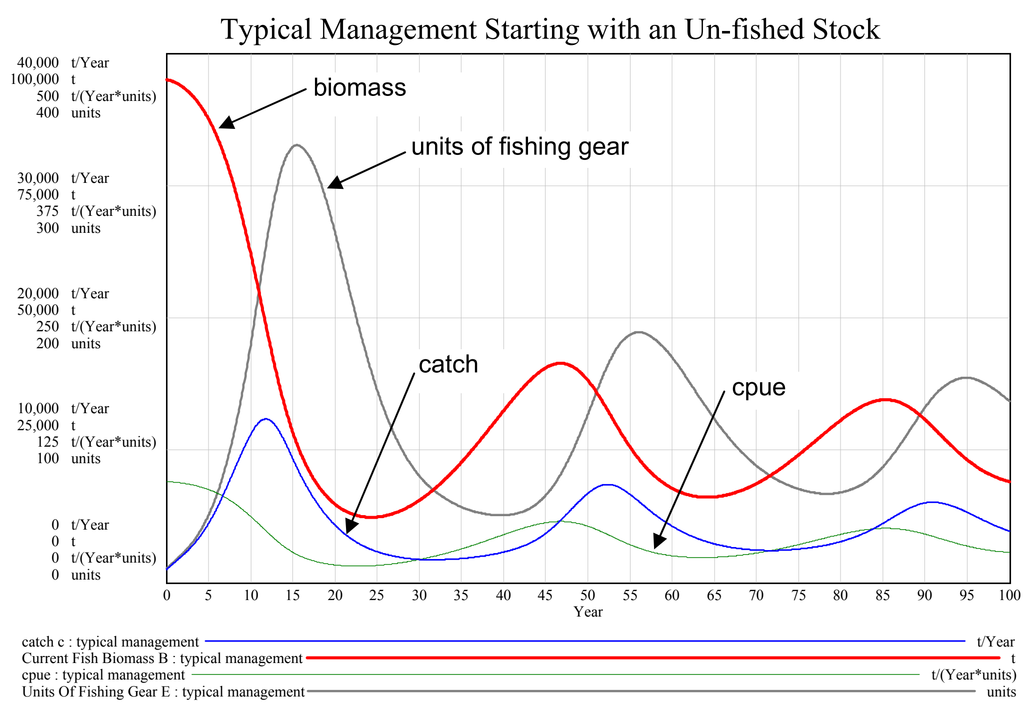

Figure 19. More typical of real management would be a management entity which never has 100% authority and is subject to variations in both administrative support and lobbying by fishers. Here management by this typical system (with a normal management authority of 70%) produces significant cycles in the fishery although again not as severe as an unmanaged situation.

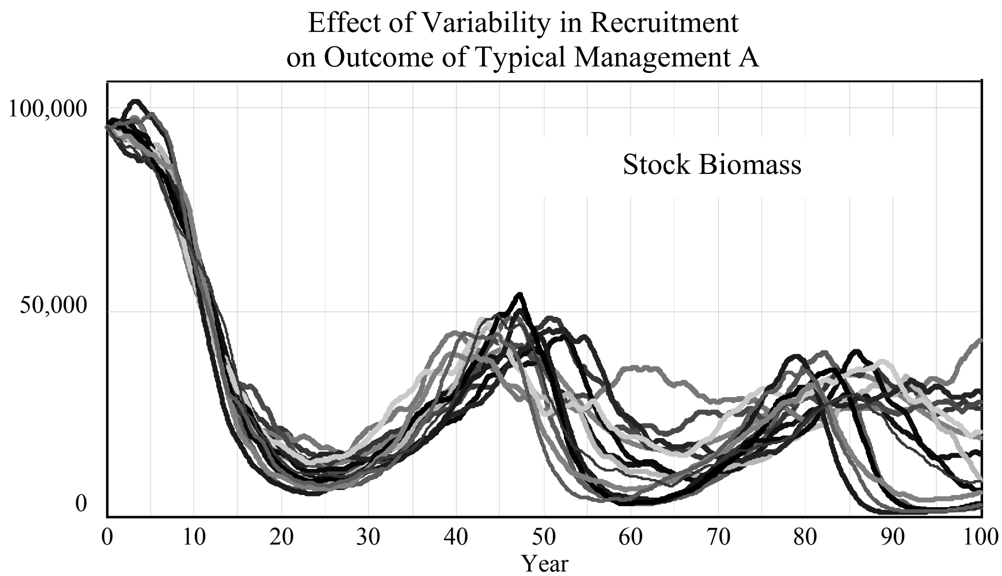

Figure 20. Graph of stock biomass showing results of 15 simulations of 'typical' management. With random variation added to recruitment the system shows significant variability but the overall cyclic pattern of the fishery remains.

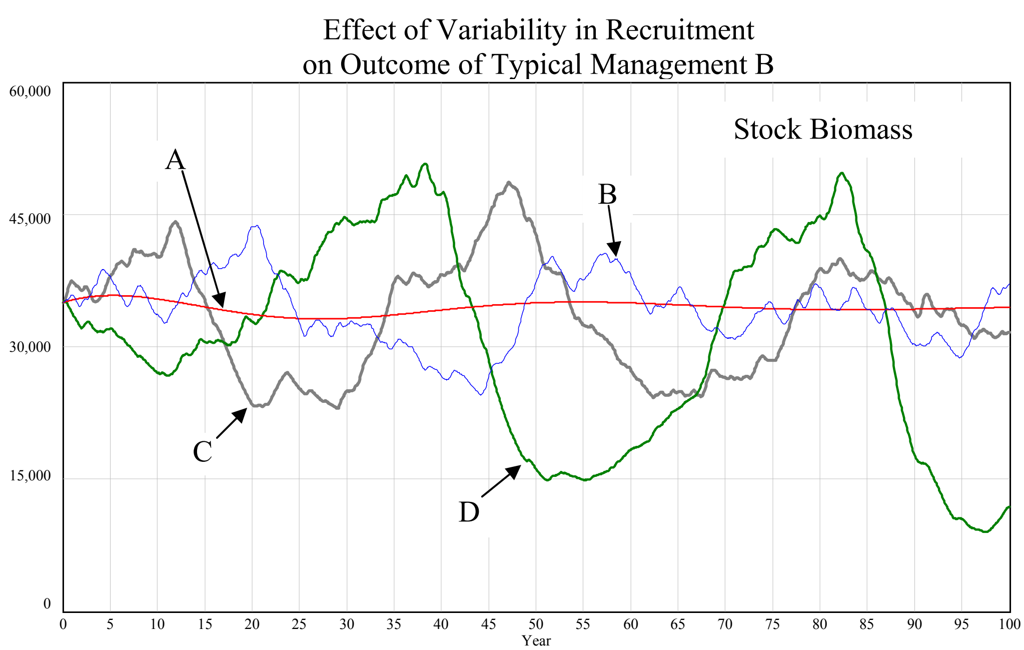

Figure 21. Four example outcomes from 'typical' management with recruitment variation. In this cases stock size and vessels numbers were in approximate equilibrium at the start of the model. Without recruit variation (line A) the fish stock remains stable. With variation the stock may remain near equilibrium (lines B and C) or, if recruitment causes sufficient change in stock size, will start to oscillate between boom and bust cycles (line D).